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Review and prospects of *Jatropha* biodiesel industry in China

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ABSTRACT

Jatropha curcas L. is chosen as an ideal biodiesel crop in China because its seed kernel has high oil content (43–61%) and it does not compete with food. Its oil is non-edible, and the trees can resist drought and grow on barren and marginal lands without using arable land. This article reviews the history of Jatropha, current development status and problems in its seeds, propagation, plantation management, oil extraction, biodiesel processing and other value-added products production techniques in China. The commercial production of seed, oil and biodiesel as well as research advancement in China is also introduced and discussed. Examples about our new bred mutant and selected high-oil-yield Jatropha varieties, high-qualified produced biodiesel, and biodiesel pilot plant are presented. Finally, future prospects of Jatropha biodiesel industry in China are discussed.

Contents

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1. Introduction

With the continuous surge in world energy consumption, energy crisis has more profound impact on global social and economic development. China's rapid rise in economy causes the sharp increase in energy demand. On the other hand, resource of fossil oil is limited and is going to running out. High oil prices, limited resources, environmental pressure and rapid-economic growth result in irreconcilable contradictions that constrain China to construct a "well-off" society and threat the national energy security. Therefore, the development and use of renewable energy have been put forward on the national agenda. President Jintao Hu and Premier Jiabao Wen gave important instructions on energy issues that led to the establishment of the "National Energy Leading Group" under the State Council and the formal authorization of the "Renewable Energy Law" in 2006 [1,2].

Biodiesel derived from renewable Jatropha and other plant oils is an ideal alternative fuel for high-qualified fossil diesel [3–7]. The development of Jatropha biodiesel industry is strategic important to promote sustainable economic growth, enhance national energy security, reduce pressure on the environment and control urban air pollution. Therefore, governments and related companies have invested in Jatropha biodiesel industry with a great passion in China Southwestern provinces such as Yunnan, Sichuan and Guizhou. By 2007, China has built up more than 2000 biodiesel production plants. China Oil and Gas Limited (PetroChina), China Petroleum Chemical Group Limited (Sinopec), China National Offshore Oil Corporation (CNOOC), other companies and governments have built or planned to build many Jatropha plantation bases (Table 1) [8].

There are several review papers about Jatropha biodiesel concerning plantation, biodiesel production and applications, economy and policy [4–7]. But, no paper is found that is systematically introducing Jatropha biodiesel and its future prospects that are focused on China. China now is the world second largest economy. Sooner or later, it would replace USA as the world number one economy and energy consumer. Thus, the development and status of biodiesel industry in China will have a global influence. The purpose of this article is to provide information about review and future prospect of China's Jatropha biodiesel industry.

2. The history of Jatropha in China

2.1. The origin of Jatropha in China

There are two different views about the origin of Jatropha in China. One is that Jatropha trees are alien species introduced to China long ago with different years, such as 500 [9], 300 [10] and 100 years [11]. Another point is that the Jatropha species are pan-tropical distributed, China is also one of the origin centers [12].

2.2. Jatropha distribution in China

Jatropha trees in China are mainly distributed in Guangdong, Guangxi, Yunnan, Sichuan, Guizhou, Taiwan, Fujian, Hainan and other Southern provinces [13,14] with natural distribution area of 1.1×10^4 ha [15–18]. In Guangxi, they mainly grow in Qinzhou, Bobai, Rongxian, Cangwu, Nanning, Yining, Longzhou, Ningming, Baise, Lingyun and Douan [16]. In Sichuan, they are distributed in Panzhihua, Yanbian, Miyi, Yanyuan, Dechang, Xichang, Huili and Jinyang [17]. In Hainan, they grow in Chengmai, Danxian, Dongfang, Baisha, Ledong, Baoting, Lingshui and Yaxian [18]. In Guizhou, they are distributed in the Red River and Pan River valleys with the natural distribution area of about 100 ha and new plantation area of more than 1500 ha in recent years [19]. Jatropha trees in Yunnan are concentrated in the West, Southwest and Central areas as well as Yuanjiang, Jinsha River, Lancang River, Nu River and Nanpan River valleys. Some trees are distributed in the areas with an altitude below 1600 m but most of them in the regions below 1200 m where trees grow well with high seed oil content [20–22]. The highest place found for Jatropha is in Yuanmou at an altitude of 1930 m.

2.3. Jatropha evolution in China

Survey shows that China's Jatropha is mainly classified into two geographical provenances: "Rainforest-type" [23] and "Savanna-type" [24,25].

"Rainforest-type" provenance is distributed in the tropical rainforest and monsoon forest climate at low latitude, low altitude, high rainfall, hot and less frost or frost-free weather conditions. Generally, they are small-trees with clear stems, average heights of 5.0–6.5 m (up to 10–12 m), ground diameters of 5.0–5.5 cm, and gray-green or dark brown barks. They flower 1–2 times per year and have umbrella- or fan-shaped crowns with large leaves, fruits and seeds, and slightly high seed oil content.

"Savanna-type" provenance is mainly distributed in Jinsha River dry-hot valley at mid-latitude and high altitude areas with intensified sunlight, sufficient hot, low rainfall, occasional frost, alternating wet and dry season, and with special climate such as cold air attack and foehn wind occurrence in the regions. Their population shows a unique advantageous, intensive and large shrub cluster of "The original ecological community" landscape. Then, groups of trees, bush or a plant are spread to the areas far from the core area of the community. It should be especially noted that "Savanna-type" Jatropha has stronger regeneration ability. Around the community, seedlings of various ages with different size are found everywhere. In a larger region, different communities form network-like continuously distributed structure along the dry-hot valley.

China's Jatropha is very sensitive to environmental changes, thus may evolve new species. During our collection of geological seed sources, we found a natural mutant in the wild that was further used to breed a new variety (Fig. 1) [26]. Results showed that its descendants through both sexual and asexual breeding methods still maintained a high degree of consistency and stability in morphological and biological characteristics, and other agronomic traits that were very different from the original species [9].

2.4. Jatropha applications in China

The early applications of Jatropha in China were direct burning its oil for lighting, and using its milk and leaves as herbal medicines for wounds or skin [27]. It was first reported in 1930s that Jatropha was used as soil and water conservation plant. Later in 1970s–1980s, Jatropha was planted as ecological trees along the

Table 1
Projects of investment in Jatropha plantation in China.

Project name	Investment scale (ha)	Project site	Investment (Yuan)
PetroChina, Jatropha oil raw material forest base in Panzhihua	12.0×10^4	Panzhihua City, Sichuan	2 billion
PetroChina, raw material forest base for Jatropha oil	3.0×10^4	Yuanyang, Yunnan	
Sinopec, Panzhihua energy forest base and biodiesel refinery	$3.0–3.5 \times 10^4$	Panzhihua City, Sichuan	
Oil forest base agreement between PetroChina and the State Forestry Administration	1500.0×10^4	five bases in Yunnan, Sichuan, Hunan, Anhui, Hebei, Shaanxi	
National Development and Reform Commission, standardized planting of Jatropha and commercial demonstration base	4.0×10^4	Southwestern Guizhou	
CNOOC, Panxi Jatropha biodiesel industry base	15.0×10^4	Panzhihua City, Sichuan	2.347 billion
CNOOC	60 KT biodiesel	Dongfang, Hainan	
Hainan CNOOC, New Energy Industrial Co., Ltd.	1500	Hainan	
Liuzhou Minghui Biofuels Co.	300 KT biodiesel	Liuzhou, Guangxi	
Hainan Honglv Zhengke bioenergy development Co.	8.5×10^4	Hainan	53 million, first investment
Sunshine Technology Group, UK	2.0×10^4	Red River basin in Yunnan	

roads and the barren hills in dry and hot valleys in Southwest China. In the early 1990s, Jatropha was selected as the preferred species for "The National Shelterbelt Project" planted along the upper and middle reaches of Yangtze River, and trial afforestation was conducted in the Jinsha River valley where certain blocks and pieces of Jatropha forest can be seen now [28]. Research and development of Jatropha oil as biodiesel raw material started in the late 1970s in China [29]. In 1970–1980s, combustion properties of Jatropha oil and tests of Jatropha biodiesel blended with fossil diesel in long-distance vehicles were carried out [30]. In 2005, national Jatropha biodiesel industry program was initialized [1].

3. Jatropha biodiesel industry development status in China

3.1. Research projects and achievements

In recent years, a number of governmental ministries, agencies and bureaus at national, provincial and municipal levels have promoted and supported Jatropha biodiesel research and applications. For example, the national research projects include "Development and utilization of Jatropha resources in Jinsha hot-dry valley region (2002–2004)", "Study of high-yield and high-qualified fuel oil plant germplasm resources and the establishment of standardized plantation demonstration bases (2005–2007)", and "Study and demonstration of the key technologies for Jatropha biodiesel industry (2007–2010)" as well as international scientific cooperation project "Energy crop development and utilization in Southwest of China (2004–2006)". At provincial level, Sichuan government supported the following projects: "Development of new technologies and new products for bioenergy (2005–2007)", "Study of large-scale tissue culture and bio-engineering breeding techniques for energy crop Jatropha (2005–2007)" and "Study of Jatropha active constituents for anti-tumor (2003–2005)". Since 2004, about 500 papers and nearly 100 patents concerning Jatropha have been published or authorized (Table 2).

3.2. Construction of Jatropha oil raw material forest bases

Jatropha trees in China are mainly distributed in Southern provinces [13,14], with natural distribution area of about

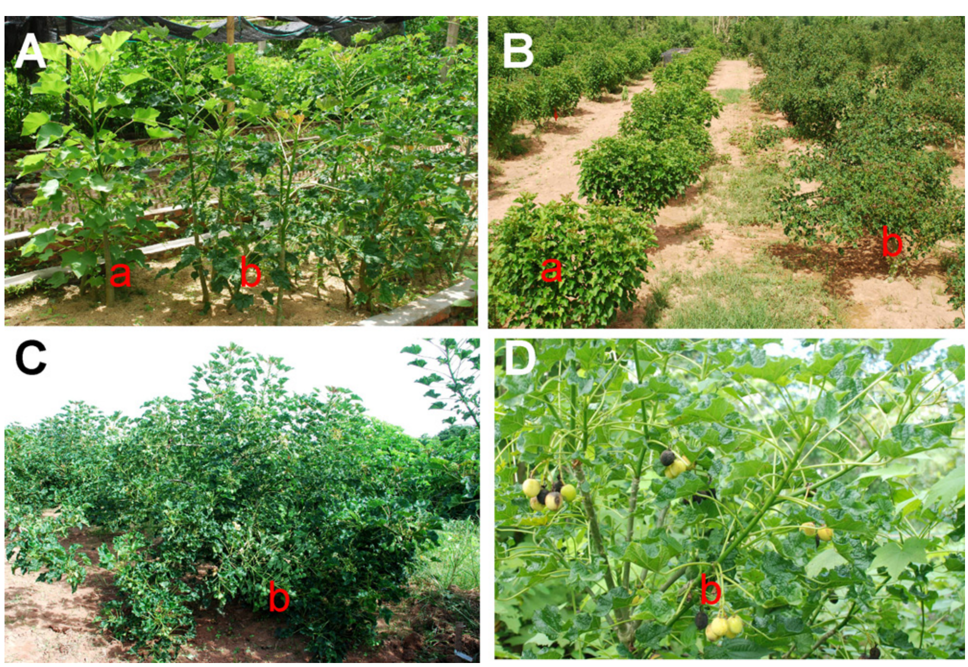

Fig. 1. New cultivar of Jatropha bred in Xishuangbanna Tropical Botanical Garden (a: old cultivar, b: new cultivar): (A) seedlings, (B) adult trees, (C) fruiting, (D) ripening fruits.

Table 2
Papers and patents for Jatropha research and development in China since 2004.

Disciplines	Pest	Cultivation and management	Cutting seedling	Tissue culture	Seed seedling	Physiological	Reproductive biology	Genetics and breeding	Seed biology	Resources	Raw material bases	Biodiesel production	Seed oil properties	Medical development	Pesticide development	Food development	Activated carbon
Paper	17	26	14	19	18	35	21	47	42	37	96	34	9	31	14	14	5
Patent	4	5	3	4	4	7	4	10	9	8	20	7	2	6	3	3	1

1.1×10^4 ha [15] and suitable plantation area of 2 million ha in Southwestern provinces of Yunnan, Sichuan, Guizhou and Guangxi. From the period of "Tenth Five-Year Plan" to "Eleventh Five-Year Plan", the total area of Jatropha biodiesel raw material forest bases has increased to 15.0×10^4 ha in China, among which 8.5×10^4 ha in Yunnan, 3.0×10^4 ha in Sichuan [17], 1.5×10^4 ha in Guizhou [19] and 1.2×10^4 ha in Guangxi [16]. In addition, Guangdong, Hainan [18], Fujian and other provinces also planted a certain area of Jatropha trees.

3.3. Propagation of Jatropha

Jatropha can be bred by both seeds and cuttings. Seed breeding has high survival rate but its seedlings will fruit only after 3–4 years. Cutting propagation has the characteristics of fast growth, more branches and early fruiting (about 1 year). In addition, tissue culture of Jatropha has been bred successful in the laboratory. This technique makes it possible to rapidly produce enough seedlings for large-scale commercial plantations.

3.3.1. Seed propagation

Jatropha is rich in seeds with large size. Seed seedlings can easily grow typical taproot with four lateral roots, and fruit after 3–4 years [31]. Afforestation is generally undertaken in early May with 3–4 seeds in a pit with spacing of 0.8–1.0 m in the ditch and riverside areas, but spacing of 0.4–0.6 m in the eroded slopes [20].

3.3.2. Cutting propagation

It is important to select mother trees, ages and diameter of cuttings, proper seedbeds as well as to disinfect them during propagation. Cutting seedbeds should be chosen from the flat lands with high water table, good drainage, medium soil fertility and loose sandy loam. Deep plowing, size reduction of soil, fertilizer use, proper moisture and disinfection for soil are needed. Robust plants aged 10 years old or less, without pests but with complete tree shapes, clean stems and healthy rich-seeds are selected as mother trees. Semi-lignified branches from the current-year grown trees or robust branches without pests from the 1 to 2 years old trees are selected as cuttings that have diameters of 1.5–3.0 cm and lengths of 12–15 cm with 2–5 buds. Cross-section of "horseshoe mouth" is cut, and coated with melted wax and soaked in carbendazim solution (50% diluted with 800 times) for 10 min. After natural drying, it is soaked again in ethylene solution (20 mg/L) for 2 h. The cuttings are planted in the spring or autumn as the following procedure: (1) using a sharp-stick whose diameter is slightly larger than the cuttings to make inclined holes in the same direction with depth of 6–8 cm and spacing 15 cm $\times$ 20 cm in the seedbed; (2) then, inserting cuttings along the hole channels to the end and pressing the soil around the actual cuttings for full access to the surrounding soil; (3) watering the cuttings to wet through the seedbed soil, and setting up a greenhouse to keep temperature at 25–28 °C and more than 80% humidity; (4) weeding manually and spraying the bed with 1% urea solution for nutritional requirements after 2–3 leaflets appear; (5) using 0.2% potassium dihydrogen phosphate to fertilize the root zone, 5–7 days before transplantation; and (6) controlling watering to harden seedlings, 10 days before transplantation. In the next year, seed yield per plant after planted will be up to 3 kg, an increase in subsequent years [20,32].

3.3.3. Tissue culture

New seedlings could be bred through tissue culture of embryos, cotyledons, epicotyls, hypocotyls, petioles, leaves, or even the tender stems with over 20 years old trees [33–40]. This technique will maintain not only the genetic stability of future generations but also rapid propagation.

After shelled, sterilized and washed, cotyledons and embryos from the seeds are stripped out and incubated in the sterile germination medium, cultured for 3 days in the dark, then transferred for light culture, and calluses are produced. After 15–30 days, 21.3–57.8% embryos grow to full seedlings. Hypocotyl with 0.5 cm^2 area and 0.5 cm length is cut from the seedling cotyledons then explanted to a shoot induction medium in order to promote the differentiation of buds. The results showed that the differentiation frequency of tissue culture buds from cotyledon and hypocotyl was 51.2% and 21.0%, respectively. In addition, tissue culture from the seedling stems could induce sprouting and rooting, and rooting frequency reached up to 78.3% [35].

The petioles and leaves of half year-old seedlings were treated at different concentrations of 6-benzylaminopurine (BA) and 3-indolebutyric acid (IBA). It was found that 0.5 mg/L BA and 1.0 mg/L IBA in murashige and skoog (MS) medium was the most effective for leaves. The reduction of IBA concentration promoted the production of shoots on hypocotyl calluses significantly. The petioles only needed low BA and IBA concentrations (<0.1 mg/L) [36].

Shoots were directly induced from epicotyl explants in MS medium with 0.1 mg/L IBA and 0.2–0.7 mg/L BA, and the highest induced rate occurred with 0.1 mg/L IBA and 0.5 mg/L BA [37]. In other work, tender stems from old trees as explants with 2.5 mg/L BA and 0.1–0.5 mg/L IBA induced the axillary buds, and further roots and full plants were developed [38].

It was reported that the endosperm and pollen were also successful cultured. Jatropha endosperm calluses were induced most effectively by 2.0 mg/L 2,4-dicholrophenoxyacetic acid (2,4-DA), followed by 1-naphthlacetic acid (NAA), IBA, indoleacetic acid (IAA). But the induction by BA and kinetin (KT) was insignificant. Addition of thidiazuron (TDZ) can promote the formation of endosperm calluses [41]. Anther developmental stage, pretreatment time, hormone combination and concentration of sucrose on the induction of Jatropha anther calluses play important roles. The mononucleus at middle-late stage is the best period for the callus induction at conditions of low temperature of 4 °C, processing time of 4–5 days and MS medium with {2.0 mg/L NAA + 0.4 mg/L KT + 9% sucrose} [42].

3.4. Evaluation of Jatropha adaptability

After planted 2–3 years, Jatropha trees start to fruit until 30–50 years old [43]. But the biological characteristics of seeds are very different in origins. Through the analyses on the seed weight, kernel percentage, oil content, growing and fruiting in different regions in Yunnan and Sichuan provinces, it was found that Yuanmou in Yunnan and Panzhihua in Sichuan are the most suitable areas for growing Jatropha with oil content of 55.5–56.4% in kernel [44–47]. Currently, a 1000 ha of Jatropha forest base for raw material has been built in Panzhihua, Sichuan [48], and 1500 ha in Guizhou [21]. Demonstration forest base is under construction in Yunnan [49,50], and trial afforestation is undergoing in Fujian. It was found that the average germination rate of Jatropha seeds was 81% and survival rate of afforestation was 92.8%. If forest was not damaged by frost and grew well in the winter, a small amount of plants would flower and fruit in September–October, and mature in December with up to 40 seeds per plant at the same year [51,52].

The mature Jatropha seeds originated from Yongsheng, Panzhihua and Honghe at different altitudes (respectively 1639, 1250, 450 m) were treated with low temperature of 8 °C, and found that Jatropha was harmed significantly with the symptoms of reduced chlorophyll content, decreased root activity and increased membrane permeability. However, seed sources from high altitude had lower degrees of cold injury [53]. On the other hand, Jatropha seedlings were also treated at different temperatures (15, 12, 8, 4 °C) and times (1, 2, 3, 4 days). The results showed that low temperature had a significant injury on seedlings, and the injury level was closely related to the temperature and time. Jatropha at low temperature decreased physical activity in order to reduce cold injury, which is an adaptive response, indicating that it has a cold resistance, especially for more than 12 years-old trees [54]. Jatropha is distributed in China at about 400–1700 m above sea level. They have different degrees for cold-resistance at different altitudes that can help us to screen cold-tolerant varieties [54–56].

Photosynthetic behaviors of 1 year-old Jatropha seedlings were studied at normal water supply and drought conditions, including the light compensation point, light saturation point, photosynthetic rate, stomatal conductance and transpiration rate [57]. It was found that photosynthetic rate presented bimodal curve-like during a day, with a significant midday depression and lower value at drought than that at normal water supply. Therefore, photosynthetic rate can be improved by reducing noon-sunlight or temperature in cultivation in the intense-sunlight hot summer.

3.5. Fundamental biotechnology research of Jatropha

Factors of (random amplification polymorphism DNA) RAPD amplification on the impact of Jatropha including buffer composition (thermus aquaticus) Taq enzyme, primer, template concentration and (polymerase chain reaction) PCR cycles were studied to determine the optimal conditions for the reaction [58]. Four methods to extract total ribonucleic acid (RNA) from the roots, stems and leaves of Jatropha were developed and the modified Zhang method was found to be the best one [59]. The best antibiotic was kanamycin at concentration of 10–25 mg/L for the screening of transgenic Jatropha [60].

3.6. Breeding and plantation demonstration

Up to now, more than 800 sources of Jatropha germplasm have been collected from home and abroad in research institutes and universities in Yunnan, Sichuan and Guizhou [9,61–63]. Over 100 copies of core or elite germplasm were marked using (inter-simple sequence repeat) ISSR [63,64]. More than 500 copies of materials were mutated with mutation and transgenic techniques by chemical mutagenesis, Co^{60} radiation and space carrying technologies [65–67]. About 10 good seed sources, 1 new variety and 10 mutants were selected and identified in the field based on the biological characteristics, economic traits, resistant characteristics and other indicators [26]. At the same time, conventional breeding and cross-breeding of Jatropha were studied [68–73]. More than 10 varieties of Jatropha were screened using multiple-selection of excellent individual plants according to the standard (seed yield > 2.5 kg/tree and kernel oil content > 65%). Seed and cutting seedling, grafting, sexual and asexual propagation techniques were developed for breeding 10 million seedlings and building 193-ha resources and parent garden, 216-ha seed propagation garden, and 8000-ha Jatropha demonstration plantation area. From June 2008 to May 2009, more than 600 domestic and foreign germplasm resources were collected, 5 good provenances were selected in accordance with the biological characteristics and economic traits, more than 500 million tree seedlings were bred, and 2793-ha area of demonstration plantation was established. We also selected 6 high oil seed sources from 80 geological provenances collected in the wild in Southwestern China. After 4 years plantation trial, we found that one of the 6 sources had the highest oil yield of 1566 kg/ha that is more than 5 times of the national best yield [74]. We have a small-scale afforestation trial of the seed source in our institute (Fig. 2).

Fig. 2. Small-scale afforestation of Jatropha in Xishuangbanna Tropical Botanical Garden.

3.7. Jatropha biodiesel industry and properties of Jatropha oil

3.7.1. Development of Jatropha biodiesel industry

As an emerging industry in China, Jatropha biodiesel industry is also demonstrating the typical market characteristics as other emerging industries at early stage. It has attracted many companies to seek business opportunities. Many large national companies including the three major oil companies (PetroChina, Sinopec and CNOOC), some foreign and local private enterprises have invested heavily in this new industry.

In June 2006, the National Development and Reform Commission approved the first three domestic Jatropha biodiesel processing demonstration projects: PetroChina Nanchong Refinery (60,000 t/year), Sinopec Guizhou Branch (50,000 t/year) and CNOOC Hainan (60,000 t/year). At the end of 2006, PetroChina and China National Cereals, Oils and Foodstuffs Corporation (COFCO) signed an agreement with the State Forestry Administration, officially launched the bio-energy forest base construction project, and established Jatropha biodiesel raw material forest bases in Yunnan, Sichuan, Guizhou and other provinces [75,76].

The Development and Reform Commission of Guizhou has approved our demonstration project for Jatropha biodiesel production. Using our patented technique, a demonstration plant built in our company (Kangda Bioenergy Technology Co., Ltd.) with 20,000 t/year biodiesel output went into trial production (Figs. 3 and 4). The Jatropha biodiesel process developed and used in Kangda has the following steps (Fig. 3):

(1) Raw material oil (Jatropha, vegetable and animal oils) and methanol (with catalyst SN-2 developed by us) were pumped into the reactor at a pre-determined flow rate controlled by a computer;
(2) The reactants reacted in the reactor for 10 s and left the reactor for the next procedure. The reactor was heated by steam or other heat sources;
(3) After reaction, the mixture went into the separator where crude glycerol was obtained. The crude glycerin can be refined further;
(4) After separation of glycerin, the mixture was purified further to remove residual glycerin and catalyst;
(5) Biodiesel was obtained after removed methanol.

Large-scale plantations of Jatropha (Table 3) and construction of biodiesel processing plants have obtained the national support as renewable energy projects. Projects have the two main characteristics. First, in addition to the national enterprise investment,

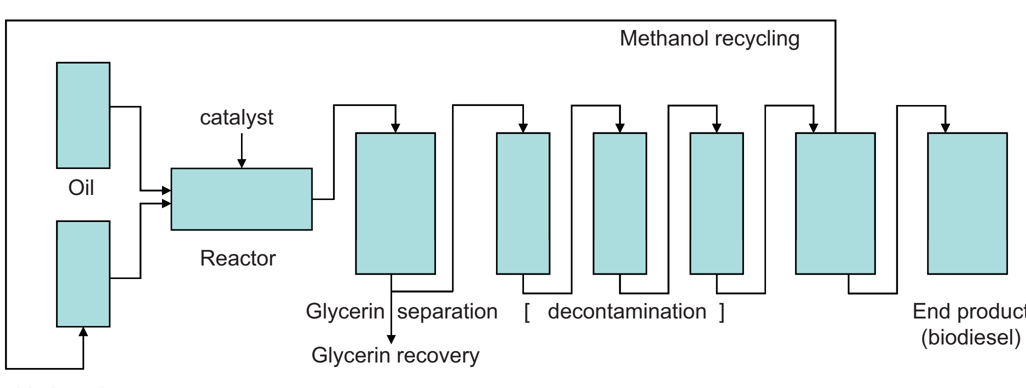

Fig. 3. Continuous Process of Jatropha Oil to biodiesel. (Kangda Bioenergy Co., Ltd.)

Fig. 4. Image of the pilot Jatropha biodiesel plant. (Kangda Bioenergy Co., Ltd.)

a number of private companies (such as Hainan Zhonghai New Energy and Industrial Development Co., Ltd., Guangxi Liuzhou Minghui Biofuels) have joined the ranks of investment. Secondly, Britain, Germany, Italy and other foreign-funded enterprises have entered this area. They attempted to use their financial strength, mature production technology, commercial experience and economic scale to occupy China's raw material bases and market share. Some projects are Sino-foreign joint ventures, such as Guizhou combined its own technology with the German Lurgi technology built up an annual output of 60,000-100,000 tons of bio-diesel processing demonstration plant. The Tiantai Biochemical Green Energy collaborated with Philippines Prize Farms Inc. and Power Generation of the Philippines has established Jatropha biodiesel raw material forest base in Philippines that was so-called the largest in the world. Up to now, China has about 0.2 million ha Jatropha tree resource (including natural forests) that can only provide 150,000 t/year seed or 45,000 t/year oil (Table 3). The suitable cultivated area for Jatropha plantation in China is about 2 million ha.

3.7.2. *Jatropha oil extraction and biodiesel performance analysis*

Zeng et al. [77] (Xiangtan university, China) used supercritical CO_2, microwave and ultrasonic to extract Jatropha oil, and it was found that supercritical CO_2 method was the most effective and clean process without the contamination of organic solvents. She et al. [78] found that oil content of the Jatropha kernel produced along Jinsha River was as high as 61%. The oil was rich in oleic acid and linoleic acid (up to 70%) with low iodine value. As each component of oil fatty acids in Jatropha seed had different melting point, the fatty acids with high melting points were easily crystallized gradually during solvent extraction and de-acidification at a given temperature. This would reduce the saturated fatty acids in oil, and lead to oil viscosity reduction [78]. Acid value can drop even lower by using anhydrous ethanol to remove free fatty acids. Crude oil with low acid value is easy to transesterify to fatty acid methyl esters (or biodiesel) without pretreatment. Biodiesel yield of 98% was achieved from Jatropha oil with sodium hydroxide as catalyst under the optimal conditions [79,80].

Jatropha oil contains alcohols, acids, ketones and other chemical components with a high fatty content and high mobility. Fatty acids include palmitic acid, stearic acid and other saturated fatty acids as well as oleic acid, linoleic acid, palmitic oleic acid and other unsaturated fatty acids (Table 4) [81]. It can blend well with diesel fuel, gasoline and ethanol. The mixture will not be separated after a long period of time [82–86].

Biodiesel properties are similar to those of fossil diesel, but its flash point, freezing point, sulfur content, CO_2 emission, particulate and other key indicators are better than those of 0 # diesel [19,84,87–90]. In recent years, Sichuan Changjiang Technology Development Co., Ltd. has granted several patents. Jatropha biodiesel has been tested in bus in Chengdu public transportation company, and the results showed that it can completely substitute petroleum diesel [49]. Our group also successfully produced high-qualified biodiesel by a two-step process with sulfuric acid pretreatment and subsequent transesterification with sodium hydroxide [91] or with the calcined hydrotalcite nanoparticles synthesized as solid base nanocatalyst that is easily recovered from products for reuse [92–95]. Without pretreatment to remove free fatty acids in Jatropha oil, we developed a one-step process to directly produce Jatropha biodiesel with ionic liquids [96] (Fig. 5).

Table 3
Areas of Jatropha plantation in China.

Planting zone	Planting area (ha)
Yunnan	Wild: 3.33×10^4, Artificial: 8.33×10^4; long-term planning: 66.67×10^4
Sichuan	Wild: 1.03×10^4; Artificial: 3.33×10^4; long-term planning: 66.67×10^4
Guizhou	Artificial: 1.5×10^4; long-term planning: 4.0×10^4
Hainan	Artificial: 0.67×10^4; long-term planning: 20.0×10^4
Guangxi	Artificial: 1.5×10^4

Note: Today, China Jatropha area (including natural forests) is about 20×10^4 ha.

Table 4
Physicochemical properties of *Jatropha* oil produced in different areas [81].

Item		Fujian	Hainan	Yunnan	Guizhou	Guangxi	Sichuan
Density (g/mL)		0.913	0.911	0.911	0.913	0.912	0.913
Refractive index (n_D^{20})		1.4701	1.4677	1.4673	1.4698	1.4685	1.4695
Acid value (mg/mL)		12.8	18.7	27.8	19.92	15.3	25.6
Saponification value (mg/mL)		191.7	189.6	196.4	188.2	193.4	192.3
Molecular weight		877.9	887.6	856.9	894.3	870.2	875.2
Fatty acid composition	Palmitic acid (C16: 0)	13.9	13.8	14.4	12.6	11.2	13.9
	Palmitic acid (C16: 1)	–	0.7	0.8	2.16	–	0.9
	Stearic acid (C18: 0)	7.8	7.1	6.3	7.1	5.2	5.9
	Oleic acid (C18: 1)	55.9	46.1	42.5	31.0	32.4	37.2
	Linoleic acid (18:2)	19.6	32.3	35.6	44.2	29.4	41.6
	Linolenic acid (C18: 3)	1.4	–	0.4	–	1.8	0.2
	Arachidonic acid (C20: 0)	1.2	–	–	–	–	0.3
	9-Eicosenoic acid (21:1)	–	–	–	2.94	6.8	–
	Erucic acid (22:1)	0.2	–	–	–	1.2	–
	Total	100	100	100	100	88	100

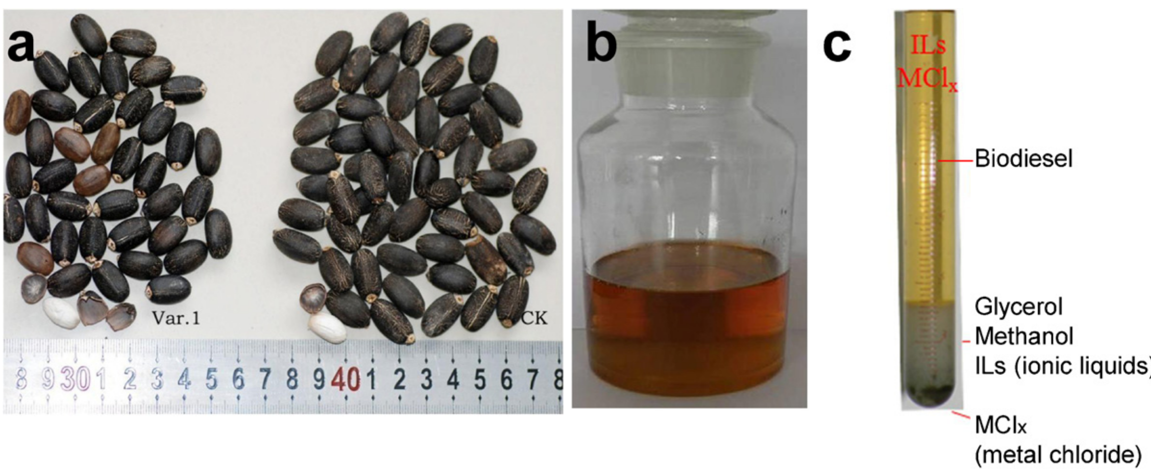

Fig. 5. Image of (a) Jatropha seeds, (b) Jatropha oil, and (c) biodiesel produced in ionic liquids in Xishuangbanna Tropical Botanical Garden.

At the same time, a method and continuous reactor was developed and patented for the biodiesel production [97,98].

3.7.3. Utilization of Jatropha

In order to make full use of Jatropha, researchers in China have carried out extensive study on comprehensive utilization of Jatropha, and have made initial progress, such as the production of natural bio-pesticides extracted from kernel [99–102], bio- and organic fertilizers, and detoxified animal feeds from Jatropha kernel cake, and activated carbon from shell.

3.7.3.1. Bio-pesticides. Yunnan University extracted active components to make bio-pesticide from kernel by conventional solvent extraction (50 L; ethanol, ethyl acetate and chloroform). Three chemical compounds were identified. Yunnan Academy of Agricultural Sciences tested the bio-pesticide on the diamondback moths, cabbage aphids and bean aphids, and found that it had a certain insecticidal activity on these three pests. The death rates of cabbage aphids at 24 and 72 h were 53.8% and 85.2%, respectively. In other work, three extractives from crude oil were found effective for aphids and cabbage worms with death rates of 66.8% and 74.3% at 72 h, respectively [101]. Wuhan Botanical Garden of Chinese Academy of Sciences, and Sichuan University have also studied Jatropha bio-pesticides [99–102]. We also developed a method to extract curcin to make a bio-pesticide that can effectively kill cabbage worms and other pests, and filed 2 patents [103,104].

3.7.3.2. Bio-fertilizers and animal feeds. Experiments showed that after oil extraction, Jatropha-cake without fermentation treatment had a negative impact on Jatropha growth. Fermentation of Jatropha-cake with the 300 strains isolated at the early stage and the effect of its fermented samples on Jatropha growth were tested, and 56 strains were screened for further study. Some strains were identified by DNA sequencing and the fermentation route was developed. Toxicity evaluation method of Jatropha-cake was established, and 32 components, including 12 toxic and 2 highly toxic components were initially isolated. Based on the understanding of the different characteristics of toxic substances, the production process of detoxification of Jatropha-cake as animal feeds was developed. Yunnan University, Yunnan Academy of Agricultural Sciences and Land Reclamation Bureau of Yunnan conducted joint R&D on organic fertilizers, biological fertilizers and toxic-free animal feeds from Jatropha-cake. Jatropha organic fertilizer was carried out field trials for cabbage heart, lettuce, cucumber and tea in Kunming and Xishuangbanna, and the results showed that the fertilizer met the national standard.

3.7.3.3. Organic fertilizers. The organic fertilizer produced by Yunnan University from Jatropha-cake was tested by the Product Testing Center of the Ministry of Agriculture, and found that it achieved "NY525-2002" national standard for organic fertilizers. Field trials for vegetables in Kunming and Xishuangbanna also reached the national relevant standards for organic fertilizers. But, the processing industrial chain for biodiesel has not yet formed. Owing to market reasons, it is difficult to collect sufficient quantity of Jatropha-cake at a reasonable price for large scale test.

3.7.3.4. Activated carbon. Kunming University of Science and Technology produced activated carbon from seed shells using microwave. A tubular lab-scale microwave reactor was developed and reaction parameters were optimized. Later, a pilot reactor with fast heating and continuously adjustable power was set up to successfully produce activated carbon based on Jatropha-shells. They had high adsorption properties and high specific surface area, their properties reached the national standards [105–107].

4. Problems of Jatropha biodiesel industry in China

Jatropha biodiesel industry still needs government support in both finance and policy. The industry is strategically important but profitability is unlikely in short-term. The initial investment is relatively large and unbearable for most of companies. In China, owing to technical bottlenecks, limited land and high labor cost, no profit has been achieved for Jatropha biodiesel projects at present. Most of enterprises just buy or rent land in the regions suitable for Jatropha cultivation for a large-scale "Enclosure Land Movement", and do business for trading Jatropha seeds [8].

Jatropha related technologies are immature, leading to slowing down its industrialization. Jatropha is often touted as biodiesel crop suitably growing in marginal land with few inputs and considerable benefits. However, this crop is currently facing three major problems: low and unstable seed yield, toxic seeds, and high labor cost for collecting seeds. Among many oil crops, Jatropha is thought the most potential biodiesel plant [5]. But the study of Jatropha is still at the initial stage of collection and use of the wild sources. Systematical studies of its biological properties, genetic characteristics, production performance and environmental adaptability of Jatropha are just starting in China.

The priority for Jatropha biodiesel industrial development is to breed excellent sources, produce good seedlings, then to cultivate Jatropha in a large-scale. The establishment of breeding and propagation techniques, plantation experiments, and demonstration forest bases is an effective way to accelerate the development of Jatropha industry. The combination of companies, farmers, research institutions and plantation bases is a good operational model to absorb social funds, use of land, labor and technological advantages to promote the industry development.

Labor cost is also an important factor. Studies showed that Jatropha fruits ripened in a wide periods of time, thus cannot be harvested once like rice and other crops. Multi-harvests are needed that increase labor cost and restrict the industrial development.

Owing to the acid value of Jatropha oil is very high (e.g., >10) [95], conventional direct transesterification with homogeneous liquid catalytic (e.g., NaOH) method will cause saponification, new processing techniques and catalysts such as two-step process, solid base nanocatalyst and ionic liquids need to be developed [91–96].

5. Prospects for biodiesel industry development

In recent years, Jatropha biodiesel as an alternative liquid fuel has been reported widely in China. Jatropha biodiesel R&D projects have been included in the national "Tenth Five-Year" and "Eleventh Five-Year" plans. Many research institutes and universities have also worked in this area. PetroChina, Sinopec, CNOOC and COFCO have invested heavily in Jatropha biodiesel processing technology and raw material forest base construction. But, as a new emerging industry, the following issues need to be properly handled or solved for its sustainable development.

5.1. Seeds

Good Jatropha seeds are the key for the commercialization of biodiesel. Since 2005, Yunnan, Sichuan, Guizhou, Guangxi and Hainan provinces had been carrying out a large number of Jatropha cultivation demonstration trials. But, the recent field investigation and related reports showed that many of the trees that were expected to enter seed production period now has not yet fruit or fruit little because the seedlings used in the plantation trials were not selected systematically. This causes many doubts for the development of Jatropha biodiesel. Therefore, at present, the priority is to breed high seed yield Jatropha varieties to promote sustainable development of the industry.

5.2. Seedling propagation techniques

At present, asexual reproduction technology is widely used in plant propagation, particularly the tissue culture technique. Indeed, this technology plays a huge role in large-scale cultivation of certain economic crops such as banana. But, Jatropha is very sensitive to external stimulus that needs further study to see if the tissue culture can work effectively. In the tissue culture, many growth-stimulating hormone substances need to be added. These substances are likely to cause the secondary mutation that has occurred in the tissue culture of banana [108].

Grafting techniques based on individual plant selection have the advantages of the yield and variety superiority from scions, but also possess deep and strong resistance characteristics of seedling root system from stocks. The techniques can achieve high seed yield that was successful applied in the production of mango, citrus and other economic forest fruits [108–111]. However, grafting cultivated plants, such as Guangxi citrus, may degrade due to the interaction between scions and stocks during their growth process. Currently, Yunnan Academy of Agricultural Sciences has developed a Jatropha grafting technique. But, maintenance of the good character of grafting scions needs to be observed for long-term.

Among the conventional cutting techniques, the hard-branch cutting was a relative successful method for Jatropha breeding, and sand-bed had a high survival rate [112]. However, the hard-branch cutting was affected by many factors, such as the cutting season, the cutting position and the lignification degree of cuttings [113,114]. It is worth to study the bud-cutting soilless culture to overcome the drawbacks from hard-branch cuttings.

5.3. Sustainable management of forest bases

Jatropha growth needs not only nutrients but also sunlight, heat, water and air, especially during the young period. High demand for sunlight and heat requires appropriate Jatropha planting density, and if for intercropping, short crops such as ginger can be planted. Water and air issue is important for Jatropha plantation in the dry and hot valley areas in Southwest China. Compacted and dry soil is another challenge for Jatropha growing in these areas. We cannot ignore Jatropha on water and air requirements due to its capability of drought resistance. Therefore, Jatropha plantation in these areas should plow land to expand the depth and scope of the loose soil in order to achieve the highest access to air and the largest water holding capacity to let trees enter into crown closure or semi-closure conditions in 1–2 years.

5.4. Investment in forests for raw materials

Currently, investment in Jatropha biodiesel industry is not enough and has the following 4 problems:

(1) Unreasonable investment budget estimation
It was mainly due to the lack of forest base-construction experience. The costs could not meet the design and market changes.

For example, estimation for fertilizers, pesticides and seeds still use the data of 10-year ago.

(2) Labor costs did not match market prices
For example, "the National Support Projects" planned labor cost per day was only 10 Yuan, practically, the price has risen to 40–50 Yuan.

(3) Inappropriate management of funds
Funding for many projects were not or not fully put in place as planned. This led to the "design in high quality, construction in low quality" for many projects that cannot achieve the desired effects.

(4) Planned product prices deviated from the current market
The current purchase price of raw Jatropha seeds is only 3 Yuan/kg, much lower than those of rapeseeds and peanuts. At such a low price, it is difficult to improve people's and enterprises' enthusiasm for plantation.

5.5. Full utilization of Jatropha

The processing technology from crude Jatropha oil to biodiesel is relative mature. Therefore, construction of plantation bases to provide enough crude oil is the key to commercialize Jatropha biodiesel. On the other hand, biodiesel used in aviation can make high profits, so novel processing technology to produce high-qualified air biodiesel is required. The sustainable development model for Jatropha industry should be satisfied the conditions that companies get profits, farmers become rich and ecology is protected.

The by-products in Jatropha biodiesel processing industry include Jatropha shell, cake and glycerol. Comprehensive utilization of them in China has made significant progress. They are successfully used to produce activated carbon, bio-pesticides, toxic-free feeds, organic fertilizers, mycorrhizal fungi fertilizers, chemicals (e.g., polyols), medical-grade glycerol and biodegradable plastics. High profitable and environmentally friendly products can help Jatropha biodiesel get more profits.

Using renewable Jatropha oil can partially solve the shortage problem of transport fuels in China. According to statistics, China currently has Jatropha resources (including natural forests) of about 0.2 million ha. Without human intervention, seed yield per hectare is about 0.75 t/year (or 0.225 t/year oil). Total seed production is only 150,000 t (or 45,000 t oil). Therefore, both Jatropha seed yield and cultivation area need increasing significantly to provide more crude oil. Chinese government has given high priority to Jatropha development. The Ministry of Science and Technology, and the National Development and Reform Commission have set up key projects to survey and plan suitable regions for Jatropha cultivation, and to carry out studies on genetic improvement and breeding high-yield varieties for Jatropha biodiesel industry. State-owned oil companies and large private enterprises are also involved in Jatropha cultivation demonstration projects.

Through investigation and experimental studies in recent years, Jatropha biodiesel industry development has made considerable progress. First of all, China still has 2 million ha land suitable for Jatropha cultivation. Secondly, through the selection and experimental studies for nearly a decade, China has developed two new good varieties. Thirdly, processing of Jatropha oil to biodiesel technology is mature.

Recent experimental studies have shown that the Chinese bred new varieties fruited at the first year, seed yield increased year by year, and entered into the rich period after 4–5 years with seed yield of 5.25 t/ha, that is 7 times that of conventional varieties (0.75 t/ha). If these new varieties are cultivated in the 2 million ha suitable land at a large-scale, after 4–5 years, about 10.5 million t/year seeds can be produced, equivalent to about 31.5 billion Yuan output according to present market price (3000 Yuan/t). Biodiesel with 3.15 million t can be produced.

The existing and potential Jatropha resources for biodiesel are very limited as compared with the national oil consumption. But the introduction of new good varieties planted in suitable non-agricultural land for a large-scale cultivation can contribute to the formation of new industrial chain in the development of Jatropha biodiesel industry.

In the production of Jatropha biodiesel (6000 Yuan/t), by-products Jatropha-cake (2.7 t/ton biodiesel) and glycerol (0.1 t/ton biodiesel) are produced. Jatropha-cake can be used to produce organic fertilizer with current price of 2000 Yuan/t. Glycerol can be used in the pharmaceutical industry or the production of other biological products (current price of 10,000 Yuan/t). As planned by the National Development and Reform Commission, if good Jatropha varieties are used for the development of Jatropha biodiesel industry, a new industry chain with 96.6 billion Yuan output will be formed after 4–5 years. It includes 31.5 billion Yuan for Jatropha seeds, 18.9 billion Yuan for biodiesel, 14.7 billion Yuan for organic fertilizer and 31.5 billion Yuan for glycerol and its bio-products. In addition, 96.6 billion Yuan output can create 1.93 million jobs.

6. Conclusions

Sufficient supply of Jatropha seeds is the key to the development of the industry. After nearly ten years of small-scale trial in China, now Jatropha biodiesel development is listed in the national industrial development plan [28,115–119]. Especially in the last five years, many national science and technology projects have been involved in Jatropha research. Jatropha biodiesel production processes and its by-products utilization technologies have made some achievements. But when Jatropha biodiesel was as an industry for commercial production or conducting large-scale R&D, it was found that we do not have enough crude Jatropha oil even for 100-ton biodiesel production. Therefore, at present and in near future, the key to Jatropha biodiesel industry development is to construct Jatropha forest bases to provide enough raw materials.

Good seedlings are the key to the construction of Jatropha forest bases for raw material. It is found that the trees planted several years ago in Yunnan, Sichuan and Guizhou provinces in the Jatropha forest bases were using the seedlings directly bred from the mother trees. They were previously grown in the dry-hot valley areas for soil erosion and water conservation works along the roads and embankments in 1970–80s in the above three provinces. Without selection, the quality of these seedlings was very low. For example, at present, some trees in the forest bases have not yet fruited and some projects stopped halfway that were related to the poor seedlings [8]. Recent advances in Jatropha study showed that varieties with high seed and oil yield were bred from the rich Jatropha resources. With the regional trials and large-scale plantation of these varieties, Jatropha seed yield in large-scale cultivation may frogleap to a new level.

Asexual propagation is an ideal method to make full use of good seed varieties. Compared with the sexual progeny, clonal descendants can keep the original integrity of plant species characteristics, narrow the differences among individuals and maintain the characteristics of stability and seed yield. This was confirmed for rubber, banana, apple and other fruit plants, as well as the early experiments for Jatropha trees in China [112–114]. Therefore, as a biodiesel crop with bright future, Jatropha breeding technologies need to be developed not only new varieties but also high quality, high yield and stable clones in order to realize large-scale plantation for providing enough crude oil for biodiesel production.

Intensified plowing is the guarantee to the success of large-scale cultivation of Jatropha. At present, some Jatropha trees grow very slow and have not yet fruited in raw material crude oil forest bases in Yunnan, Sichuan, Guizhou and other provinces. The problems are related to not only seed sources but also growing conditions and proper plantation technical measures. Early studies showed that Jatropha had high requirements for temperature, sunlight and rainfall [9]. We should consider and plan such conditions in advance for the forest base construction. Technical requirements for Jatropha afforestation include loose soil and sufficient space for root growth in order to let Jatropha have deep root systems and great shoot growth so that the seedlings can survive through the dry season and have good growth potential in the coming year.

As compared with the national oil consumption (252 million t for 2009), the current (45,000 t) or potential (3.15 million t) Jatropha oil output is or will be very low. Therefore, at national level to see, Jatropha biodiesel is complementary for other key potential alternative transportation fuels (e.g., bio-ethanol, synthetic liquid fuels from coal). But, in some subtropical or tropical regions in China such as in Yunnan, it may play an important role in replacing fossil diesel. Thus, we should plan, model and optimize energy supply and demand systems at all levels (e.g., village [120], provincial and national) according to local, national and global resources and consumption as well as economic and social development [120–123]. Then, we can plan the Jatropha developmental strategy at all levels from the whole system point of view.

We can conclude that Jatropha biodiesel industry is still at its early development stage in China. Its development needs not only new technical advances in seeds, propagation, plantation management and oil processing techniques, but special policy (e.g., subsidy and tax exemption), comprehensive applications and ecology effects should also be considered for its sustainable development.

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